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SSS-R-86-8033 MDA903-82-C-0350

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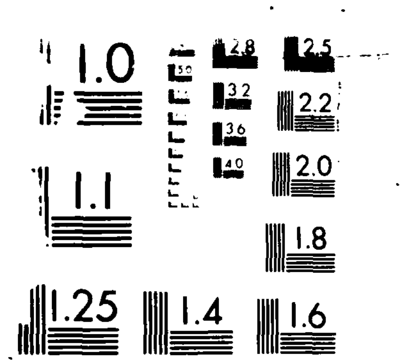
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SSS-R-86-8033

MODELING OF NETWORK IDENTIFICATION CAPABILITY

T. G. Barker
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J. M. Savino

Final Report

Submitted to:

Defense Advanced Research Projects Agency
1400 Wilson Boulevard
Arlington, Virginia 22209

July 1986

Approved for Public Release,
Distribution Unlimited.

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(619) 453-0060

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SECURITY CLASSIFICATION OF THIS PAGE

AD-A178 969

APR 0 6 1987

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE:

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for Public Release, Distribution Unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): SSS-R-86-8033

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: S-CUBED A Division of Maxwell, Labs., Inc.

6b. OFFICE SYMBOL *(If applicable)*:

7a. NAME OF MONITORING ORGANIZATION: Defense Advanced Research Projects Agency

6c. ADDRESS *(City, State and ZIP Code)*: P. O. Box 1620, La Jolla, California 92038

7b. ADDRESS *(City, State and ZIP Code)*: 1400 Wilson Boulevard, Arlington, Virginia 22209

8a. NAME OF FUNDING/SPONSORING ORGANIZATION:

8b. OFFICE SYMBOL *(If applicable)*:

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: MDA903-82-C-0350

8c. ADDRESS *(City, State and ZIP Code)*:

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
6271E	2A10		

11. TITLE *(Include Security Classification)*: MODELING OF NETWORK IDENTIFICATION CAPABILITY

12. PERSONAL AUTHOR(S): Barker, T. G., Rodi, W. L., Savino, J. M.

13a. TYPE OF REPORT: Final Report

13b. TIME COVERED: FROM 820622 TO 831122

14. DATE OF REPORT *(Yr., Mo., Day)*: July 1986

15. PAGE COUNT:

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*: Seismic Network; Network Identification; Event Discrimination; Computer Modeling

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

The objective of this project was to develop a computer program for modeling - seismic event identification capability of an existing global network of seismograph stations. In addition the program is to provide for evaluation of the impact on the overall network identification capability resulting from modifications to the netw in the form of additions, deletions or geographic relocations of stations.

The computer program that resulted from this project is referred to as NICE (Network Identification Capability Evaluation). The NICE program consists of fou major elements which are executed in series. The overall approach is a Monte Carlo simulation in which events are generated from random series, "recorded" in a network as synthetic seismograms and then "analyzed" for discrimination scores. The first element is the module which generates a series of events whose statistical properties -

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☒ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

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22c. OFFICE SYMBOL: DSO

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

19. ABSTRACT (continued)

match those of observed events. The second module computes amplitudes and travel times for these events using synthetic seismograms. These data are analyzed in the third module and given discrimination scores. The output of this module is a bulletin which resembles a discrimination bulletin. Finally, the performance of the discriminants as applied to the synthetic bulletin can be examined using plots and lists displayed by the fourth module. The characteristics of the synthetic bulletin can also be compared with actual observations of the network using the fourth module. The NICE program is operational on a Gould 6031E computer at S-CUBED and on a VAX 11/780 at the DARPA Center for Seismic Studies (CSS) in Arlington, Virginia.

TABLE OF CONTENTS

I. INTRODUCTION

The objective of the work described in this report is to develop a computer program for modeling the seismic event identification capability of an existing global network of seismograph stations. In addition the program is to provide for evaluation of the impact on the overall network identification capability resulting from modifications to the network in the form of additions, deletions or geographic relocations of stations.

Early work on this topic was conducted at the Defense Advanced Research Projects Agency (DARPA) by Drs. Ralph W. Alewine and Carl F. Romney. Based on the results of their efforts it was decided to proceed with the design and implementation of an interactive program that would achieve the above stated objectives.

The initial approach adopted was to construct an algorithm that combines a statistical analysis of existing discrimination data with analytical network detection and location modeling techniques. More specifically, identification probability versus m_b curves for an existing network were to be estimated from an analysis of past discrimination performance. In order to predict the identification curves for a modified network, the curves for the existing network had to be changed to reflect expected differences in the detection and location capabilities of the existing versus the modified network.

After considerable effort the analytical approach proved to be intractable in large part owing to the complex dependence of seismic discriminants on the varied properties of seismic phases used in the application of these discriminants as well as the number and distribution of detecting stations. Subsequently, based on suggestions by Dr. Robert R. Blandford of DARPA, a different approach (Monte Carlo) was adopted and implemented in the network identification modeling program. The resulting program is referred to as NICE (**N**etwork **I**dentification **C**apability **E**valuation)

In the Monte Carlo approach the source properties of seismic events in a geographic region of interest are generated by random selection. The NICE program then computes synthetic seismograms of these events for a specified network of seismograph stations and determines discrimination scores based on the synthetic seismograms. This approach has several strong advantages, the most important of which is that the elements of the problem affecting network identification capability are included naturally and directly and can be tested independently for accuracy. The elements are divided into three major categories:

1. source and propagation,
2. network-controlled,
3. processing.

The methodology incorporated in the NICE program allows for the straightforward inclusion of such effects as the reduction of surface wave amplitudes with event focal depth (and the corresponding reduction in M_s:m_b), the shift in corner frequency with source dimension (and corresponding changes in M_s and m_b), the relative frequency content of P and S waves, focal mechanisms and source type (explosion, earthquake, spall model, etc.). In addition, because of the modular structure of the program new identification criteria can be readily included. Should the new criteria require that seismic phases not currently computed in the synthetic seismogram section of the program be included, they may also be added in a straightforward way. In general, the program has been structured for use in an interactive mode with as much flexibility as possible. The NICE program is operational on a Gould 6031E computer at S-CUBED and on a VAX 11/780 at the DARPA Center for Seismic Studies (CSS) in Arlington, Virginia.

The following section of this report gives a detailed description of the structure and flow of operations in the NICE program. In the final section a Users' Manual is given to facilitate operation of the program.

II. THE NICE PROGRAM

The NICE program consists of four major elements which are executed in series, as shown in the flow chart in Figure 2.1. The overall approach is a Monte Carlo simulation in which events are generated from random series, "recorded" in a network as synthetic seismograms and then "analyzed" for discrimination scores. The first element is the module which generates a series of events whose statistical properties match those of observed events. The second module computes amplitudes and travel times for these events using synthetic seismograms. These data are analyzed in the third module and given discrimination scores. The output of this module is a bulletin which resembles a discrimination bulletin. Finally, the performance of the discriminants as applied to the synthetic bulletin can be examined using plots and lists displayed by the fourth module. The characteristics of the synthetic bulletin can also be compared with actual observations of the other networks using the fourth module. In the following, we briefly describe these four modules. Details of the calculations are given in the appendices.

2.1 THE EVENTS MODULE

The events generator creates a list of earthquake epicenters, depths, origin times, scalar moments, and fault orientations. The values in the list are members of statistical ensembles whose parameters have been deduced from observations. We have endeavored to formulate the program so that each set of parameters can be checked independently against an observable. We have allowed for regionalization of the parameters, a feature that is very important for modeling the differences in the performance of discriminants in different tectonic regions of the USSR. For example, the distribution of events with depth in the Kurile-Kamchatka area differs greatly from that in the Hindu Kush, and thus the depth discriminants behave differently.

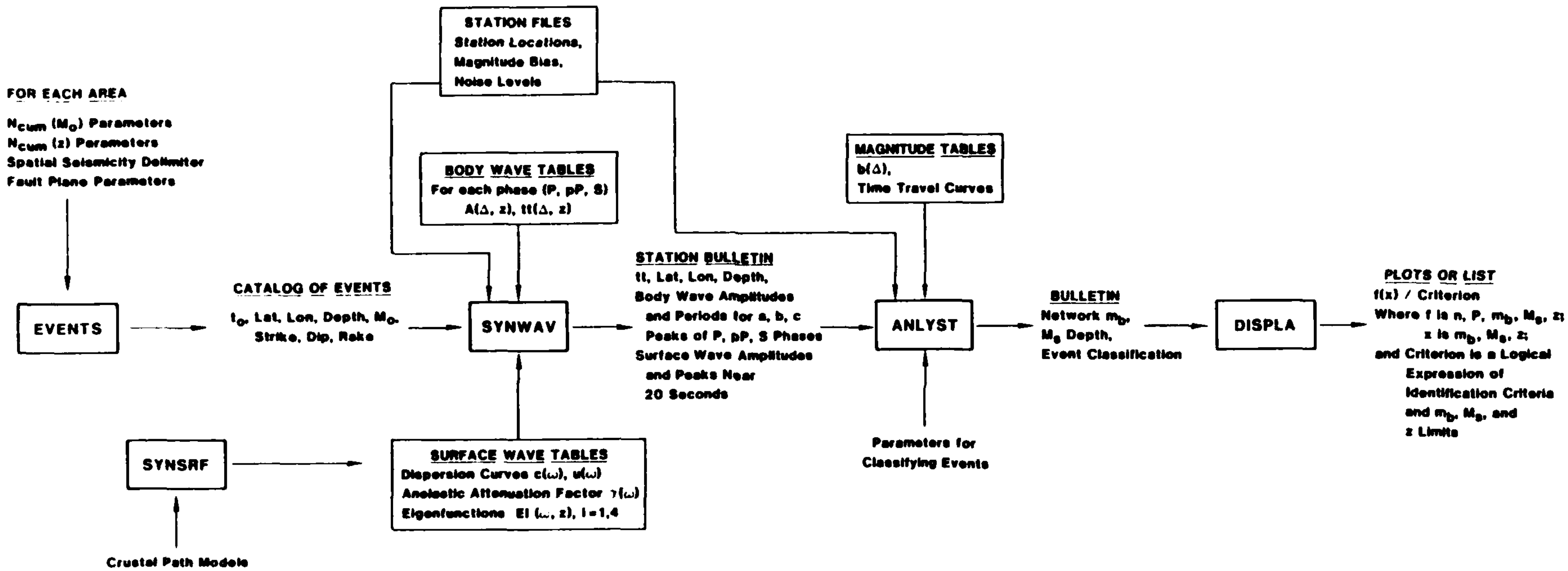

Figure 2.1. Flow chart of Network Identification Capability Evaluation (NICE) program.

Epicenters are distributed uniformly within boxes on the surface of the globe. The sides of the boxes are great circles intersecting at right angles. The user specifies two latitude, longitude pairs and the length of the side normal to the line connecting the pairs. The formulas for finding the epicentral coordinates are given in Appendix A. Maps made from synthetic distributions of events specified in this way are very similar to the actual distribution of events reported by the Soviets to the International Seismological Center. We find that five boxes provide a good description, with the boxes encompassing the seismic areas of the Caucasus, the Hindu Kush, far-eastern Siberia, Tibetan border-Lake Baikal area, and Kurile-Kamchatka.

The distribution of focal depths is specified by a piece-wise linear function which is the cumulative number of events occurring at or below a given depth. Appendix A gives the algorithm for focal depth. The distributions observed on the Soviet bulletin are fit well by this specification, often with a single linear segment.

Fault orientation is described by the strike, dip and rake of the slip vector. Each quantity is distributed uniformly within a standard deviation of a mean value. In most seismic areas, a few faulting mechanisms dominate, making the choice of parameters apparent. In areas where there are extensive seismic determinations of the fault plane (such as done by Murphy and Lambert, 1985, for the Hindu Kush and Pamirs), we have reliable values for the distribution.

The recurrence interval of events at a given scalar moment is assumed to follow a Poisson distribution, as suggested by Lomnitz (1966). The cumulative number of events occurring per year at or above a given magnitude is predicted by this distribution. This is typically described for magnitudes with "a" and "b" values (intercept and slope on a number versus magnitude plot). Analogous values for log moment are used by EVENTS to determine the origin time and scalar moment of each event. See Appendix A for details. As it would be tedious and perhaps error prone to require the user to enter these parameters interactively and since the parameters are not changed often, the EVENTS program reads files containing the parameters specific to each seismic area.

2.2 THE SYNWAV MODULE

The SYNWAV program reads the list of source characteristics created by EVENTS, computes synthetic body and surface wave seismograms for these events at the stations in the network, and measures the amplitudes and travel times from the synthetic records. These results are used to construct a station bulletin which will be used in the next module in the series, ANLYST. Details of the formulation are given in Appendix B.

The first step is to read several files containing data used in the calculations. This includes a station file which includes station locations and long and short period noise parameters. Amplitude and travel time tables are read for the body wave calculations and dispersion and eigenfunction files are read for surface waves.

The body wave calculations begin with computing a time series which is the convolution of the instrument response and t* attenuation operator for each phase (P, pP, S). We assume at this stage that propagation introduces no other pulse distortion. The body wave calculations then follow these steps for each event.

1. The azimuth and range from the source to each station is computed.

2. The amplitude decay rates and travel times are looked up in the tables giving the values as functions of distance and focal depth. The ray parameters are found by numerically differentiating the travel time curves with respect to distance (Equation B1.3).

3. A frequency-independent factor due to each ray's position on the focal sphere is computed assuming that the source radiates from a point (point double-couple approximation). These are the factors a^P, etc., in Equation (B1.4).

4. The instrument t* time series is convolved with a moment function in Equation (B1.5) The convolution is scaled by the radiation pattern and decay rate.

5. The peak-to-peak amplitudes and periods are "measured" for the a, b, and c swings on the record.

6. The noise preceding each phase is found from the maximum peak-to-peak value in a random series of duration 10 seconds with mean and standard deviation prescribed by the station file. In addition, noise with the same properties is added to the amplitude measurements.

For the body wave calculations, we assume that the major part of the propagation path, the mantle, introduces no pulse distortion (the mantle transfer function has a flat spectrum). For surface waves however, dispersion causes the shape of the wave train to change significantly with range. Thus we must compute a seismogram for each station-event pair, rather than scaling amplitudes as is done for body waves. The most time consuming part of a surface wave calculation is finding the dispersion curves and corresponding eigenfunctions for the fundamental mode. To reduce computation time, the group and phase velocities for the chosen propagation path are computed by the SYNSRF program (a general purpose surface wave program written at S-CUBED) for a chosen propagation path and stored on a file. In addition, the eigenfunctions for a suite of source depths are calculated and stored. SYNWAV then reads the eigenfunctions and interpolates for the values of source depth required by the events catalog. The interpolated values are then included in the surface wave formulation shown in Appendix B. The peak value whose period is between 18 and 22 seconds is found and written to the output catalog. As with body waves, a noise estimate is found for the background and a value added to the amplitude measurement.

2.3 THE ANLYST MODULE

The primary function of the ANLYST module is to apply particular network rules for assigning discrimination scores to the events generated by EVENTS based upon the seismograms seen at the stations in the network as computed by SYNWAV. ANLYST reads amplitude, period, travel time and noise

data from SYNWAV output files and computes additional quantities needed for discrimination scoring. These quantities are signal-to-noise ratios, the number of stations with good recordings, the body and surface wave magnitudes, pP step-out, and travel time residuals found from locating the event. The travel time residuals result from a nonlinear least squares inversion of the travel-time data (read from tables). The location program uses the actual source coordinates written by SYNWAV as starting values for the iterative procedure so convergence is rapid. As required by particular network procedures for assigning the travel time score, residuals are computed with the depth fixed at the free surface and with the depth a free parameter in the inversion. Where applicable, locations are done including the S phase. The program then applies the particular network rules and writes a bulletin with the discrimination scores.

2.4 THE DISPLA MODULE

The final module, which was demonstrated at the Center for Se[illegible] Studies in November 1983, allows the user to list and plot the results [illegible] analysis described above or the observations of an operating network [illegible] program has a sophisticated command processor wh[illegible] specification of the type of displays required. The types [illegible] divided into two groups

1 event detection and discrimination [illegible]

2 seismicity parameters

A third type of plot that may be [illegible] depths of individual events [illegible]e

3 M_s versus m_b, z versus m_b [illegible] that satisfy a given condition

The data on a given plot are always based on events that meet one or more conditions specified by the user. A condition is a restriction on as many as eight properties of an event (i.e., a condition has eight "subconditions"):

1. m_b,
2. M_s,
3. depth,
4. geographical area in which the event was located,
5. year in which the event occurred,
6. "identification status" assigned to the event,
7. discrimination criterion on which the status is based,
8. type of event (mainshock versus aftershock).

III. USERS' MANUAL FOR NICE

This section is a users' manual for the NICE program. There are actually four programs: **events**, **synwav**, **anlyst** and **displa**. Each is documented in UNIX "man" format.

The programs are linked together through files. There are 10 files and they serve as the principal inputs and outputs for the programs. The manual in this section includes "man pages" for these files, in addition to the programs. Particular file names referenced in this section are those used in the testing and initial calibration runs of the program. They are included as illustration.

The methods and algorithms for the NICE programs are described in Section II and Appendices A and B.

PROGRAM

events . . . Generate a random seismic event catalog.

SYNOPSIS

events **-a** < area-list > **-y** < year-spec > **-n** < num-of-events >
-s < parameter-file > **-o** < output-file >

DESCRIPTION

Program **events** generates a pseudo-random catalog of earthquakes, distributed in space, time and magnitude according to a given set of input seismicity parameters. The command-line arguments are defined below. (Each of these arguments is optional, and takes a default value when omitted.)

< area-list >.

The argument < area-list > is a list of geographic areas for which events are to be generated. Each entry in the list refers to one of five predefined areas:

hkA . . . Hindu Kush (Subarea A)
hkB . . . Hindu Kush (Subarea B)
hkC . . . Hindu Kush (Subarea C)
hkD . . . Hindu Kush (Subarea D)
hk . . . Hindu Kush (All subareas)

A given area is referred to by the short name shown above (e.g., **hkB**) or by a number from 1 to 5, which selects according to the above order (e.g., **hkB** is 2). Entries in < area-list > must be separated with whitespace; e.g., '**-a** 1 2 3'

The default value of < area-list > is '1'.

< year-spec >.

< year-spec > is a specification of which years events are to be generated for. There are two acceptable forms:

(1) Two numbers separated by a colon (no whitespace), which indicate the first and last years desired; e.g., '**-y 73**:**77**'.

(2) A single number, giving the total number of years desired. In this case, the years are numbered from 1; e.g., '**-y** 4', which is equivalent to '**-y** 1:4'.

The default value of <year-spec> is '1'.

<num-of-events>.

This argument is the total number of events to be generated. The distribution of seismicity with respect to time is adjusted such that <num-of-events> are generated over the time period indicated with <year-spec>. Event origin times are incremented by the recurrence intervals Δt, given in Appendix A.3.

The default value of <num-of-events> is 0.

<parameter-file>.

This is a filename "prefix" for the input seismicity parameter files. There must be one such file for each geographic area specified by <area-list>. The program expects each such file to be named as follows:

<pardir>/<parameter-file>.<area-name>

<pardir> is the name of a directory which the user must define with a Unix environment variable called **PARDIR.** This may be accomplished with the Unix command **setenv** as follows:

setenv PARDIR <pardir>

<parameter-file> is supplied as an argument of the **-s** flag. <area-name> is the name of the area selected through the **-a** flag

For example, if you use

setenv PARDIR /usr/ljacks/bunyon
events -s myparms -a hkA hkC

then **events** will expect seismicity parameters to be in the two files:

/usr/ljacks/bunyon/myparms.hkA
/usr/ljacks/bunyon/myparms.hkC

The content and format of the seismicity parameter files is described in the manual entry "Seismicity File."

The default value of < parameter-file > is **'par'**.

< output-file >.

Filename for the output event catalog. The full file pathname is

< catdir > / < output-file >

where < catdir > is the name of a directory which the user must define with a Unix environment variable called CATDIR. this may be accomplished with the Unix command **setenv** as follows:

setenv CATDIR < catdir >

For example, if you use

setenv PARDIR /usr/ljacks/bunyon
events -o mycatalog

then **events** will write the event catalog it generates to the file

/usr/ljacks/bunyon/mycatalog

If the **-o** flag is omitted, the event catalog is written to "standard output": i.e., the CRT screen or a redirected output file.

The content and format of the output event catalog is described under manual entry "Event Catalog."

PROGRAM

synwav . .. Generate a synthetic arrival bulletin.

SYNOPSIS

synwav

DESCRIPTION

Program **synwav** generates a synthetic arrival bulletin for a given seismic network and set of earthquakes. For each earthquake, the bulletin contains a report of the various seismic wave arrivals (Rayleigh, P, pP or S) detected by each station of the network. The report includes amplitude, arrival time and signal-to-noise information about each arrival.

The arrival bulletin is output to the following file:

/USERS/geop/barker/nice/files/stnbul/hkC

See manual entry "Arrival Bulletin" for a description of the file content and format.

All input to **synwav** is from files. The type and name of each input file follows.

Station File

This file contains the names and locations of the network stations. (See manual entry "Station File".) The filename is

/USERS/geop/barker/nice/files/stnfiles/john

Event Catalog

This file contains the catalog of events for which arrivals are to be generated. It includes the location, depth, size and slip parameters of each event. (See manual entry "Event Catalog".) The file name is

/USERS/geop/barker/nice/files/events/hkC

Earth Structure.

This file contains the earth structure used for calculating surface-wave and body-wave responses. (See manual entry "Structure File" for more information.) The filename is

/USERS/geop/barker/nice/files/str/ekz

Path File.

This file contains surface-wave response information for the assumed earth structure model. (See manual entry "Path File" for further information.) The filename is

/USERS/geop/barker/nice/files/eigfiles/ekz3

Body Wave Table Files.

There is one body wave table file for each body wave to be modeled (e.g., P). The file contains a tabulation of travel time and amplitude as a function of epicentral distance and event focal depth. (See manual entry "Table File.") The filename containing the body wave table for the wave type <wave> is given as

/USERS/geop/barker/nice/files/bwtables/tab<wave>

<wave> is one of **P, pP or S**.

Body Wave Reference Files

These files supplement the body wave table files. There is one reference file for each type of body wave. It contains information regarding the reference values of moment, position on the radiation pattern and reciever amplification used in generating the amplitude table contained in the corresponding body wave table file. (For further information, see the manual entry "Reference File.") The filename containing the body wave reference data for the wave type <wave> is given as

/USERS/geop/barker/nice/files/reftab/ref.<wave>

Long Period Instrument File.

This file contains the frequency response of the long-period instrument at each station. It is assumed to be station-independent. (See manual entry "Instrument File.") The filename for the long-period response is

/USERS/geop/barker/nice/files/inst/kono.lpz

Short Period Instrument File.

This file contains the frequency response of the short-period instrument at each station. It is assumed to be station-dependent. (See manual entry "Instrument File.") The filename for the short-period response is

/USERS/geop/barker/nice/files/inst/kono.spz

PROGRAM

anlyst . . . Generate a synthetic discrimination bulletin.

SYNOPSIS

anlyst

DESCRIPTION

Program **anlyst** generates a synthetic discrimination bulletin for a given seismic network and set of earthquakes. The bulletin is obtained by applying detection, location and discrimination algorithms to the data in an arrival bulletin. (See manual entry "Arrival Bulletin".) For each event reported in the arrival bulletin, **anlyst** produces a record for the discrimination bulletin which contains an estimate of the event's origin time, location and magnitudes as well as a set of "scores" which summarize the results of discrimination analysis.

The discrimination bulletin produced by **anlyst** is output to the following file:

/USERS/geop/barker/nice/files/aftac/hkC

See manual entry "Discrimination Bulletin" for a description of the file content and format.

All input to **anlyst** is from files. The type and name of each input file follows.

<u>Station File</u>.

This file contains the names and locations of the network stations. (See manual entry "Station File".) The filename is:

USERS/geop/barker/nice/files/stnfiles/john

Arrival Bulletin.

This file contains the reports of seismic wave arrivals (e.g., P, pP, S, Rayleigh) at the network stations from various events. (See manual entry "Arrival Bulletin".) The filename is:

/USERS/geop/barker/nice/files/stnbul/hkC

Body Wave Table Files.

anlyst requires one body wave table file for each of the body waves: P, pP, S. Each file contains a tabulation of travel time and amplitude as a function of epicentral distance and event focal depth. (See manual entry "Table File".) The filename containing the body wave table for the wave type <wave> is assumed to be

/USERS/geop/barker/nice/files/bwtables/tab <wave>

where <wave> is one of **P, pP or S**.

PROGRAM

displa . . . Query and display a discrimination bulletin.

SYNOPSIS

displa

DESCRIPTION

displa is an interactive program for displaying the data in a discrimination bulletin. The bulletin contains a summary of discrimination results for a given set of events. Displays take the form of plots or tables showing various breakdowns of these results. (Plots require a Tektronix 4014 terminal.)

The content of a given display is governed by two types of information specified by the user. The first type of information is a set of conditions determining a subset of the entire set of events in the bulletin. For example, the user might specify the subset of events which satisfy the two conditions: (1) the event has been correctly identified by the network and (2) its focal depth is less than 50 km. More than one such subset might be involved in a given display.

The second type of information specifies the event properties to be displayed for those events in the specified subset(s). Examples of such properties are the distributions of the events with respect to magnitude and depth.

Now we define these two types of information in detail.

Event Subsets

A given subset of events is defined by conditions on the following eight event properties:

C1 The *type* of the event: main shock, aftershock, or an event which has been "ignored" for analysis.

C2 The *class* of the event, as determined by its discrimination scoring results.

C3. The *discriminants* whose scores are "credited" with determining the class of the event.

C4. The geographical *area* where the event has been located. The possible areas have been predefined. Arbitrary conditions on latitude and longitude are not allowed.

C5. The *year* in which the event occurred.

C6. The body wave magnitude, m_b, determined for the event.

C7. The surface wave magnitude, M_s, determined for the event.

C8. The estimated depth, *z*, of the event.

A condition on the latter three quantities (m_b, M_s, z) consists of a minimum and maximum value.

The actual commands for specifying event subsets through the above conditions are described later.

Functions to Display.

One may display the following event properties: m_b, M_s, z, and event counts and proportions as a function of these three variables. These quantities can be displayed in many different ways.

To describe the possible displays, let x and y each denote one of the variables m_b, M_s or z. Let A and B denote two subsets of events which the user has defined through a list of conditions. The data from the events in A and B may be displayed as the following functions:

F1 $N_A^C(x)$: the *cumulative count* of events in A with respect to x, i.e., $N_A^C(x_0)$ is the number of events in A with $x \geq x_0$

F2. $N_A(x)$: the *incremental count* of events in A with respect to x. Given a specified increment Δx, $N_A(x_0)$ is the number of events such that $x_0 \leq x < x_0 - \Delta x$. Thus,

$$N_A(x) = N^C_A(x) - N^C_A(x - \Delta x)$$

F3. $P^C_{A|B}(x)$: the *cumulative ratio* of the number of events in A*B to the number in B. A*B denotes the intersection of subsets A and B. Note that

$$P^C_{A|B}(x) = N^C_{A*B}(x) / N^C_B(x)$$

Observe that N_{A*B} is the number of B events which are also A events. Thus A*B is a subset of B and $P^C_{A|B}$ must be between 0 and 1.

F4. $P_{A|B}(x)$: the *incremental ratio* of the number of events in A*B to the number in B:

$$P_{A|B}(x) = N_{A*B}(x) / N_B(x)$$

F5. y(x): distribution of events (from subset A) in the x-y plane, e.g., $M_s(m_b)$ defines the classical M_s versus m_b plot.

Commands in **displa**

After executing **displa**, the user is queried for the name of a file containing a discrimination bulletin. She will then be asked to indicate whether this file is formatted or unformatted. (If the file has been generated by **anlyst**, it is *formatted*.) After this, the user operates **displa** through a set of commands.

There are four types of commands recognized by **displa**.

1. Commands to define conditions on event subsets.

2. Commands to display data from the discrimination bulletin.

3. Commands to set parameters for displays.

4. Utility commands.

Condition Commands (A Conditions).

Earlier we defined various quantities one could display for a subset of events we called A or for two subsets A and B: e.g., N_A, $P_{A|B}$. At any given time during a run of **displa**, A and B are defined in terms of conditions on eight variables (see C1-C8 above). In this section we discuss commands for the user to specify "A conditions"; i.e., conditions which determine the event subset A.

When the user initiates a run, a set of default conditions are invoked. These define the subset A of events to be all inclusive; i.e., A is the entire set of events in the bulletin. To redefine A, the user may specify her own conditions with one or more commands of the form:

<cond-var> = <A-cond-value>

(The equals sign (=) is optional.) For <cond-var> one uses one of the following keywords:

ty	...	to specify event *types*
cl	...	to specify event *classes*
di	...	to specify *discrimination criteria* for event classes (explained below)
ar	...	to specify *areas*
yr	...	to specify *years*
mbr	...	to specify m_b *ranges*
Msr	...	to specify M_s *ranges*
zr	...	to specify *z ranges*

At any given time, a condition command for a given variable automatically overrides any previous definition for that variable, whether it was a default or user specified. Conditions on other variables, however, are not affected.

There are two styles for <A-cond-value>, depending on which variable one is specifying. For **mbr**, **Msr** and **zr**, <cond-var> specifies a minimum and maximum value:

< cond-var > = < min-value > : < max-value >

This command restricts the subset A to include only events having

< min-value > ≤ < cond-var > < < max-value >

For example, to include events with M_s between 5.0 and 6.5 (not including 6.5), one should use the command

Msr = 5:6.5

The second style for < A-cond-value > selects one or more items from a fixed menu of choices. This style applies to **ty**, **cl**, **di**, **ar**, and **yr**. The simplest form is to specify a single item, i.e.,

< cond-var > = < item >

For example,

yr = **74**

To select two or more items, one uses

< cond-var > = < item$_1$ > + < item$_2$ > + ... + < item$_N$ >

In this way, an event is in subset A if it matches *any* of the items given. For example, to select events in the presidential election years from the 1970's

yr = **72 + 76**

In general, one may use any logical expression involving the menu items and the logical operators + (or), * (and) and (not). Thus **72 + 76** means "events in the years 72 or 76". As another example, to select events from all years except 1973 (i.e., "not 73") one would use

yr = ~ **73**

Let us now define the complete menu for each condition variable.

M1. Types: **ma af ig**

ma ...	The event is a *main* shock.
af ...	The event is an *after* shock.
ig ...	The has been *ignored* (not analyzed).

M2 Classes: **c1 c2 c3 c4 c5 c6 c7 c8**

The classes are defined in terms of numerical discrimination scores as follows. The following definitions are hierarchical: i.e., the first test which the scores satisfy determines the class.

c1 ...	one or more 1's
c2 ...	two or more 2's.
c3 ...	*one 2*
c6	two or more 4's: or one 4 and one or more 3's
c5	one 4, or two or more 3's
c4	one 3
c7	one or more 5's: or one or more 6's
c8	no scores given

M3 Discriminants **d1 d2 d3 d4 d5 d6**

M4 Areas **kkn kks es hk cau**

These are abbreviations for geographic areas. defined as follows:

kkn	...	Kurile-Kamchatka north (longitude > 140°E, latitude > 48°N)
kks	...	Kurile-Kamchatka south (longitude > 140°E, latitude < 48°N)
es	...	Eastern Siberia (85° < longitude < 140°E)
hk	...	Hindu Kush (85°E < longitude < 60°E)
cau	...	Caucasus (longitude < 60°E)

M5. Years: **73 74 75 76 77**.

A condition on discriminants is actually an elaboration on the condition on class. Each class requires that certain discrimination score values occur. Discriminants that have the proper score values are "credited" with the event having been assigned to its class. The condition on discriminants thus restricts the subset of events to include only those event for which the specified discriminants receive credit for the event's class. For example, events which are in class 1 by virtue of the discriminant d4 are selected with

cl = c1
di = d4

Given the definitions of the classes, this is equivalent to the set of events for which discriminant d4 received a score of 1. As another example, to select events for which *both* d2 and d4 receive credit for *either* class 1 or class 2, one uses

cl = c1 ~ c2
di = d2 * d4

This is satisfied by either (a) events in class 1 for which d2 and d4 *both* have a score of 1, or (b) events in class 2 for which d2 and d4 both have a score of 2.

Note that a simple conjunction of items using * only makes sense in the case of conditions on discriminants. That is, two or more discriminants can simultaneously receive credit for an event's class. However, an event cannot, for example, be simultaneously in two or more areas or in two or more years. Thus, for example **ar = kkn * kks** yields the empty set of events.

As a convenience for experienced users, the menu items for each condition variable are given a fixed order, and the user may use the "min-max" style to select a set of contiguous items from a menu. For example, the ordering of years is chronological, so

yr = **73:78**

is equivalent to

yr = **73 – 74 – 75 – 76 – 77 – 78**

As a further convenience, the menu items are numbered and the user may select items by number (as long as she has figured out the numbering). For example,

ar = 2

is equivalent to

ar = **kks**

As a final convenience, the alias **all** has been defined to denote the "all-inclusive" condition for any variable. For example,

ar = **all**

denotes '**ar** = **kkn** – **kks** – **es** – **hk** – **cau**', and

mbr = **all**

denotes '**mbr** = -1000:1000' (i.e., or some other suitably large magnitude range).

To learn the current setting of a given condition variable, type

<cond-var> = ?

e.g., '**ar** = ?'.

Condition Commands (B Conditions).

When the user initiates **displa**, the subset B is undefined. To define B, an extended syntax of condition commands is recognized:

<cond-var> = <A-cond-value> / <B-cond-value>

<A-cond-value> specifies a condition on subset A, as described above. <B-cond-value> specifies a condition with respect to the same variable on event subset B.

Once a B condition has been explicitly defined for one variable, **displa** automatically invokes a default value for the B conditions of the other variables. The default is the corresponding A condition. Thus,

<cond-var> = <A-cond-value>

is the same as

<cond-var> = <A-cond-value> / <A-cond-value>

For example, the following sequence defines A and B to have events in the same two areas, but with different classes:

ar = kkn - kks
cl = c1 / c1:c7

In this example, $P_{A|B}$ would be the fraction of events in the Kurile-Kamchatka areas which are in class 1, among those from the same two areas which are in classes 1 through 7.

Condition Commands (Multiple Conditions)

It is possible to define multiple versions of the subset A. When this is done, **displa** automatically generates multiple functions on a single display, thus facilitating the comparison of data. For example, suppose one wanted to compare data from events in three different geographic areas. One would then define three subsets A_1, A_2 and A_3 which satisfied a common set of conditions except for the condition on area. A display of a given function would then automatically show three versions, one for each area. If one requested a display of $N_A(m_b)$, for example the three functions $N_{A1}(m_b)$, $N_{A2}(m_b)$ and $N_{A3}(m_b)$ would appear on the same display.

Multiple subsets A may differ with respect to only *one* condition variable. The command syntax for defining multiple versions of the desired variable is

<cond-var> = <A_1-cond-value>, <A_2-cond-value>

Thus, multiple condition values are separated by commas. Each value follows the rules outlined earlier. As an example, suppose one wants to make an area-by-area comparison of class 1 events from 1973. Then one would define multiple A subsets with

ar = **kkn**, **kks**, **es**, **hk**, **cau**
cl = 1
yr = **73**

These commands imply that A_i, i = 1, ..., 5, are defined by the same conditions on class and year, but different conditions on area.

The reader should be careful to distinguish between combining items with "+" and defining multiple items with ",". The "+" syntax merges two items into one while "," separates individual cases. To emphasize the difference, note the following example which uses both devices. Suppose we wish to compare events from two geographic regions, the Kurile-Kamchatka region versus the rest of the Eurasia. We would then define two subsets of events by specifying multiple conditions on area.

ar = **kkn** - **kks**. **es** - **hk** - **cau**

Thus, the first region (subset A_1) combines **kkn** and **kks**. The second subset combines events from three areas.

Multiple B subsets may also be defined, but only implicitly; i.e., multiple items may not appear behind a '/'. Multiple versions of B are implicitly defined for a variable when multiple A conditions have been given for the variable but no B condition has been given. For example, suppose we set every condition variable to **all**, except for the following

ar = **kkn**. **kks**. **es**

cl = **c1** **all**

This defines three subsets A_1, A_2, A_3 and three subsets B_1, B_2, B_3. The A's contain events in class 1, while the B's contain events in any class (i.e., from all eight classes). A_1 and B_1 contain events in area **kkn**, A_2 and B_2 for **kks**, and so on. Given these subsets, if one were to ask for a display of $N_A(m_b)$, she would get three functions $N_{Ai}(m_b)$, $i = 1,2,3$. Each is the number of class 1 events in its respective area. If one were to ask to display $P_{A|B}(m_b)$, then she would get three functions $P_{Ai|Bi}(m_b)$, $i = 1,2,3$. $P_{A1|B1}(m_b)$ is the fraction of class 1 events in **kkn** among all events in **kkn**. And so on.

Now compare this to the following

ar = **kkn** **kks** **es** **all**

cl = **c1**

This defines three subsets A_1, A_2, A_3 and *one* subset B. The A's are as before, the number of class 1 events in each of three areas. B is number of class 1 events in all areas combined. (To understand this, recall that '**cl** = **c1**' is the same as '**cl** = **c1** **c1**'.) Now $N_A(m_b)$ defines the same three functions as before. $P_{A|B}(m_b)$ though refers to $P_{A1|B}(m_b)$, $P_{A2|B}(m_b)$, and $P_{A3|B}(m_b)$. $P_{A1|B}$ is the fraction of class 1 events in area **kkn** among class 1 events in all areas combined.

As an additional convenience for defining multiple conditions, there is an alias ! which selects each and every menu value for a condition variable. For example,

ar = **!**

is equivalent to **ar** = **kkn**, **kks**, **es**, **hk**, **cau**.

<u>Display Commands</u>.

There are two commands for displaying data:

plot <function>
list <function>

plot produces a standard x-y plot containing one or more curves. **list** produces a table with one column for x-axis data, followed by one or more columns for y-axis data. The data which are displayed are defined by the argument <function>.

The argument <function> takes the general form <y>(<x>), where <y> denotes a dependent variable and <x> denotes an independent variable. The choices for <x> are:

$\mathbf{m_b}$ $\mathbf{M_s}$ **z**

with obvious meaning. The choices for <y> are:

nc ...	cumulative count of events in subset A, N^c_A
n ...	incremental count of events in subset A, N_A
pc ...	cumulative ratio of events in subsets A and B, $P^c_{A\|B}$
p ...	incremental ratio of events in subsets A and B, $P_{A\|B}$

For plots (but *not* lists) <y> may also be

$\mathbf{m_b}$ $\mathbf{M_s}$ **z**.

When A and/or B are multiply defined, multiple plots or tabulations are automatically produced for $A_1, A_2, \ldots$ and B or $B_1, B_2, \ldots$ as described in the previous section.

Examples of display commands are

plot nc (**mb**)
list p (**Ms**)
plot Ms (**mb**)

As a convenience, **displa** allows the combination of display and condition commands, with the forms

plot <function> <condition_1> <condition_2> ...
list <function> <condition_1> <condition_2> ...

Each of the optional arguments <condition_1>, ... is a condition command as defined above. It behaves exactly as if it had been issued prior to the display command, including the fact that it alters the definitions of A and B for future commands (until overridden). Thus

plot pc ($\mathbf{m_b}$) **ar** = 1 **cl** = **c1** / **all**

is equivalent to

cl = **c1** / **all**
ar = 1
plot pc (**mb**)

Parameter Commands.

Parameter commands set certain parameters for plots and lists. There are two types of such parameters:

1. Plot/table limits: i.e., the minimum and maximum values of the x-axis variables for which data are displayed

2. Plot/table increments: i.e., the sampling increment for the x-axis variable, determining the spacing between displayed data.

There are three possible x-axis variables (m_b, M_s, z), so there are six commands for setting display parameters:

mblim = < min-value > : < max-value >
Mslim = < min-value > : < max-value >
zlim = < min-value > : < max-value >

and

mbinc = < value >
Msinc = < value >
zinc = < value >

To learn the current setting of these parameters, type:

< parameter > = ?

e.g., '**mbinc** = ?'.

Utility Commands.

The following additional commands are recognized by **displa**

help . . . print out some information which might help the user select his next command

quit . . . terminate this session with **displa**

FILE TYPE

Arrival Bulletin . . . report of seismic arrival information from a set of events at a set of stations

CREATED BY

Program **synwav**

USED BY

Program **anlyst**.

DESCRIPTION

The arrival bulletin contains the arrivals reported by a network for each of several seismic events. The arrival information includes arrival times, amplitudes, periods, and noise levels for various seismic phases.

The arrival bulletin is an ASCII file consisting of records separated by new-lines. The records are in groups, each group corresponding to one event and its arrivals. Within a group is a set of records for each station, each set containing information about the Rayleigh wave arrival and various body wave arrivals.

More specifically, the bulletin is organized as follows

(For each event
  Event header record
  (For each station
    Station record
    Surface-wave record
    Body-waves header record
    (For each type of body wave
      Body-wave record 1
      Body-wave record 2

The formats of the various records follow

Event Header Record.

Columns	Fortran Format	Data Description
1-51	(a)	Event information (time, location, depth, moment, focal mechanism)
52-55	i4	Number of stations recording event

(a) See manual page on "Event Catalog"

Station Record.

Columns	Fortran Format	Data Description
1-10	a	Station identifier
11-20	1pe10.2	Event-station distance (degrees)
21-30	1pe10.2	Event-station azimuth (degrees c.w. from north)
31-40	1pe10.2	Event-station back-azimuth (degrees c.w. from north)

<u>Surface-Wave Record.</u>

Note: The displacement, period and travel-time given are those of the maximum amplitude cycle of the Rayleigh wave in the 18's to 22's period range

Columns	Fortran Format	Data Description
1-10	1pe10.2	Zero-to-peak displacement (meters)
11-20	1pe10.2	Time-domain period (seconds)
21-30	1pe10.2	Travel-time (seconds)
31-40	1pe10.2	Zero-to-peak long period noise (meters)
41-50	1pe10.2	Travel-time standard deviation (seconds)

<u>Body-Wave Header Record.</u>

Columns	Fortran Format	Data Description
1-5	i5	Number of body wave arrivals
5-10	i5	Number of peaks (or troughs) reported per wave (always 3)

Body-Wave Record (First of Two).

Columns	Fortran Format	Data Description
1-10	a	Wave type ('P', 'pP' or 'S')
11-40		Onset arrival time
11-14	i4	Year
15-18	i4	Month
19-22	i4	Day
23-26	i4	Hour
27-30	i4	Minute
31-40	f10.2	Seconds

Body-Wave Record (Second of Two).

Columns	Fortran Format	Data Description
1-10	1pe10.2	Zero-to-peak short period noise (meters)
11-20	1pe10.2	Travel-time standard deviation (seconds)
21-50		Zero-to-peak displacements of wave (meters)
21-30	1pe10.2	Peak 1
31-40	1pe10.2	Peak 2
41-50	1pe10.2	Peak 3
51-80		Time-domain period of wave (seconds)
51-60	1pe10.2	Peak 1
61-70	1pe10.2	Peak 2
71-80	1pe10.2	Peak 3

FILE TYPE

Discrimination Bulletin — report of location and discrimination results for a set of earthquakes

CREATED BY

Program **anlyst**

USED BY

Program **displa**

DESCRIPTION

The discrimination bulletin is an ASCII file consisting of records separated by new-lines. Each record corresponds to one earthquake. The format of a record is as follows:

Columns	Fortran Format	Data Description
1-5	i5	Event number
6-8	i3	Year number of origin time (earliest year in bulletin is 1, second earliest is 2, etc.)
10-12	i3	Area number of location
14-16	i3	Focal depth (kilometers)
18-20	i3	Body wave magnitude, m_b (hundredths of a magnitude unit)
22-24	i3	Surface wave magnitude, M_s (hundredths of a magnitude unit)
26-28	i3	Azimuth of major axis of location error ellipse (degrees c.w. from north)

30-32	i3	Length of semi-major axis of location error ellipse (kilometers)
34-36	i3	Length of semi-minor axis of location error ellipse (kilometers)
38-40	i3	Event type flag
42-44	i3	Score for discriminant 1
46-48	i3	Score for discriminant 2
50-52	i3	Score for discriminant 3
54-56	i3	Score for discriminant 4
58-60	i3	Score for discriminant 5
62-64	i3	Score for discriminant 6

FILE TYPE

Event Catalog . . . location and source parameters for a set of earthquakes.

CREATED BY

Program **events**.

USED BY

Program **synwav**

DESCRIPTION

The event catalog is an ASCII file consisting of records separated by new-lines. Each record corresponds to one earthquake. The format of a record is as follows:

Columns	Fortran Format	Data Description
1-6	i6	Event number
7-19		Event origin time
7-8	i2	Year
9-10	i2	Month
11-12	i2	Day
13-14	i2	Hour
15-16	i2	Minute
17-19	i3	Seconds
20-32		Event location
20-24	i5	Latitude (thousandths of degrees from equator)
25	a	Hemisphere ('n' or 's')
26-31	i6	Longitude (thousandths of degrees from Greenwich)
32	a	Hemisphere ('e' or 'w')

33-35	I3	Event depth (kilometers)
36-39	I4	Logarithm of event moment (newton-meters)
40-51		Focal mechanism
40-43	I4	Strike (tenths of degrees c.w. from north)
44-47	I4	Dip (tenths of degrees below horizontal)
48-51	I4	Rake (tenths of degrees c.c.w. from horizontal)

FILE TYPE

Instrument File . . . a seismic instrument response

CREATED BY

User.

USED BY

Program **synwav**.

DESCRIPTION

This file contains a seismic instrument response in the form of poles and zeros in the complex frequency plane.

Let s be the complex Laplace transform parameter ($i\omega$). Then the instrument response as a function of s is given by:

$$I(s) = A (s - z_1) \ldots (s - z_n) / [(s - p_1) \ldots (s - p_m)]$$

where $z_1, \ldots, z_n$ are the zeros and $p_1, \ldots, p_m$ the poles of the response function.

The instrument file is an ASCII file consisting of records separated by new-lines. The data are in Fortran 77 "free" format (i.e., 'read *') Therefore, arbitrary white-space may be used to separate the items on each record (including extra new-lines)

The contents of the file, record by record, are as follows

Record 1:
< comment >

Record 2:

< A >

Record 3:

< num-of-poles >

Record 4:

< real-pole$_1$ > < imag-pole$_1$ >

Record 5:

< real-pole$_2$ > < imag-pole$_2$ >

. . .

Record 3 – m:

< real-pole$_m$ > < imag-pole$_m$ >

Record 4 – m:

< num-of-zeros >

Record 5 – m:

< real-zero$_1$ > < imag-zero$_1$ >

Record 6 – m:

< real-zero$_2$ < imag-zero$_2$ >

.

Record 4 – m – n:

< real-zero$_n$ > < imag-zero$_n$ >

In the above, subscripts m and n stand for the variables < num-of-poles > and < num-of-zeros >, respectively.

The variable < comment > is a character string of length 80 or less. We identify the other variables with the variables in the equation for I(s) above, as follows:

$A = \langle A \rangle$

$m = \langle \text{num-of-poles} \rangle$

$n = \langle \text{num-of-zeros} \rangle$

$p_j = \langle \text{real-pole}_j \rangle + i \langle \text{imag-pole}_j \rangle$

$z_j = \langle \text{real-zero}_j \rangle + i \langle \text{imag-zero}_j \rangle$

FILE TYPE

Path File . . . surface wave path and source response functions

CREATED BY

User.

USED BY:

Program **synwav**

DESCRIPTION

This file contains a tabulation of Rayleigh wave path responses as a function of frequency, and source excitation eigenfunctions as a function of source depth and frequency.

This is a binary file containing variable length records. The content of each record is as follows:

Record 1:
<comment>

Record 2:
<num-of-frequencies>

Record 3:
<freq$_1$> <freq$_2$> ... <freq$_n$>
<phase-vel$_1$> <phase-vel$_2$> ... <phase-vel$_n$>
<group-vel$_1$> <group-vel$_2$> ... <group-vel$_n$>
<a-sub-r$_1$> <a-sub-r$_2$> ... <a-sub-r$_n$>
<ellip$_1$> <ellip$_2$> ... <ellip$_n$>
<γ_1> <γ_2> ... <γ_n>

Record 4:
<src-depth$_1$> <src-α_1> <src-β_1> <src-ρ_1>
<src-μ_1> <src-λ_1> <src-σ_1>

Record 5:

$< eigf_{111} >$ $< eigf_{211} >$ . . . $< eigf_{n11} >$
$< eigf_{112} >$ $< eigf_{212} >$ . . . $< eigf_{n12} >$
$< eigf_{113} >$ $< eigf_{213} >$ . . . $< eigf_{n13} >$
$< eigf_{114} >$ $< eigf_{214} >$ . . . $< eigf_{n14}$

Record 6:

$< eigf_{121} >$ $< eigf_{221} >$ . . . $< eigf_{n21} >$
$< eigf_{122} >$ $< eigf_{222} >$ . . . $< eigf_{n22} >$
$< eigf_{123} >$ $< eigf_{223} >$ . . . $< eigf_{n23} >$
$< eigf_{124} >$ $< eigf_{224} >$ . . . $< eigf_{n24} >$

. . .

Record 4 − m:

$< eigf_{1m1} >$ $< eigf_{2m1} >$ . . . $< eigf_{nm1} >$
$< eigf_{1m2} >$ $< eigf_{2m2} >$ . . . $< eigf_{nm2} >$
$< eigf_{1m3} >$ $< eigf_{2m3} >$ . . . $< eigf_{nm3} >$
$< eigf_{1m4} >$ $< eigf_{2m4} >$ . . . $< eigf_{nm4} >$

End-of-file

In the above, subscript n stands for < num-of-frequencies >. Subscript m is the number of source depths (which are counted as they are read).

The meanings of the above variables follow.

< comment >

A character string of length 80 or less.

< num-of-frequencies >

The number of frequency samples at which the response functions are tabulated. (Fortran type 'integer'.)

< $freq_i$ >

The i^{th} sampling frequency (hertz). (Fortran type 'real'.)

<phase-vel$_i$> <group-vel$_i$> <a-sub-r$_i$> <ellip$_i$> <γ_i>

These are the Rayleigh wave responses at the frequency <freq$_i$>. These response functions are those defined by Harkrider (1970). From left to right, they are:

1. phase velocity (m/s)
2. group velocity (m/s)
3. A_R (m/Nt)
4. ellipticity
5. γ_R (km^{-1})

(All are Fortran type 'real'.)

<src-depth$_j$>

The j^{th} sampling source depth for eigenfunctions. (Fortran type 'real'.)

<src-α_j> <src-β_j> <src-ρ_j> <src-μ_j> <src-λ_j> <src-σ_j>

The earth properties at the source depth <src-depth$_j$>. From left to right, they are:

1. P wave velocity (m/s)
2. S wave velocity (m/s)
3. Density (kg/m^3)
4. Shear modulus (Pa)
5. Lame' parameter λ(Pa)
6. Poisson's ratio.

(All are Fortran type 'real'.)

<eigf$_{ijk}$>

The surface-wave eigenfunction of the k^{th} type ($k = 1,2,3,4$) at the i^{th} frequency and j^{th} source depth. (See Appendix B.2.) (Fortran type 'real'.)

FILE TYPE

Reference File — reference values for amplitude tables, for a particular body wave

CREATED BY

User.

USED BY

Program **synwav**.

DESCRIPTION

This file is associated with a particular body wave (e.g., P) and is an adjunct to the body wave table file for the same wave (see manual entry "Table File").

This is an ASCII file. It contains three numbers in Fortran 77 free format (i.e., "read *"). The numbers may be separated by arbitrary white-space (blanks, tabs or new-lines). The three numbers are the reference values for which the amplitude tables were computed. They may be used to scale the amplitude tables. The three numbers are the

1. The reference moment (N-m).
2. The reference value on the radiation pattern.
3. The reference receiver amplification function.

FILE TYPE

Seismicity File . . . parameters of the seismicity distribution in a given geographic area

CREATED BY

User.

USED BY

Program **events**.

DESCRIPTION

This file contains seismicity parameters for one geographic area. It is an ASCII file consisting of records separated by new-lines. The data in the file are assumed to follow Fortran 77 free-format rules (i.e., 'read*'). Thus, the spacing between items is not important, as long as certain items, as indicated below, begin a new record.

To assist the user with documentation, this file may contain "comment fields," which are stripped out by NICE before the Fortran free-format read is called. A comment field begins with the sharp (#) character and ends with end-of-record (new-line or end-of-file).

The contents of the seismicity parameter file are as follows:

Beginning-of-file
<a-factor> <b-factor> <min-moment>
New-line
<num-of-depth-points>
New-line
< z_1 > < F_1 >
< z_2 > < F_2 >
. . .
< z_n > < F_n >

New-line
<box-lat$_1$> <box-lon$_1$>
<box-lat$_2$> <box-lon$_2$>
<box-width>
<strike-mean> <strike-sigma>
<dip-mean> <dip-sigma>
<rake-mean> <rake-sigma>
End-of-file

"New-line" indicates where new-line (carriage-return) characters are required in the input. Specifically, the following data items must begin a new line: <num-of-depth-points>, <z_1> and <box-lat$_1$>. For considerations of readability, the user is also allowed to insert new-lines between other data items as well, as long as none of the three mentioned above is omitted. As mentioned above, commend fields are also allowed.

The variables appearing above are defined as follows. Refer to Appendix A for mathematical details.

<u><a-factor>, <b-factor>, <min-moment></u>

These are parameters of the distribution of seismicity with respect to seismic moment. Let N(M) denote the expected number of earthquakes occurring in the geographic area of interest, having a seismic moment greater than M. Then, this function is given by

log10 N = <a-factor> - <b-factor> * M, M >= <min-moment>
N = 0, M < <min-moment>

<u><num-of-depth-points></u>

This variable is the number of points defining the depth distribution of seismicity. <num-of-depth-points> must be at least 2, but not greater than 25. [Note: the maximum, currently 25, is given by Fortran parameter "maxz".]

$<z_1>$ $<F_1>$ $<z_2>$ $<F_2>$ . . . $<z_n>$ $<F_n>$.

This list is a sampling of the distribution of seismicity with depth. The number of sample points, shown here as 'n' is identically <num-of-depth-points>. The pairs ($<z_i>$, $<F_i>$), $i = 1, \ldots, n$, are assumed to be samples of the function F(z), defined to be the fraction of earthquakes which occur below depth z. By definition, the following constraints on these values must be obeyed:

$$<z_1> \; = 0$$
$$<F_1> \; = F(0) = 1$$
$$<F_n> \; = 0$$
$$<z_i> \; > \; <z_{i-1}>, \; i = 2, 3, \ldots, n$$
$$<F_i> \; \leq \; <F_{i-1}>, \; i = 2, 3, \ldots, n$$

F(z) is assumed to be linearly interpolated between sample points.

$<\text{box-lat}_1>$ $<\text{box-lon}_1>$, $<\text{box-lat}_2>$, $<\text{box-lon}_2>$, $<\text{box-width}>$.

These parameters define the spatial distribution of seismicity for this geographic area. Earthquake epicenters are assumed to be uniformly distributed with a box-like region on the earth's surface.

EXAMPLE

Here is an example of a seismicity-parameter file:

```
# Seismicity parameter file for Hindu-Kush, subarea A.
#
# Seismicity versus moment parameters
#
  1.593  0.565  4.e14  #  a-factor, b-factor, min-moment
#
# Seismicity versus depth parameters
#
 2  # number of points in distribution
#        z     F
         0.    1.
        50.    0.
#
```

```
# Epicenter box:
#
#        lat1     lon1     lat2     lon2     width
         37.4     69.9     39.2     72.0     1.2
#
# Fault plane distribution:
#
          28.      10.      # strike mean and std dev
          34.      10.      # dip mean and std dev
         -80.      10.      # rake mean and std dev
```

The latitude-longitude pair <box-lat$_1$>, <box-lat$_2$> are the coordinates of point P_1, shown in Figure A.1, and similarly for P_2. Indices of the points on the corners of the box increase counter-clockwise from P_1. The arc-length <box-width>, the quantity ℓ_{14} on Figure A.1, is the length of the arc connecting P_1 and P_4. The units of these quantities is degrees.

<u><strike-mean>, <strike-sigma></u>

These variables are the mean and standard deviation of a uniform distribution for strike, in degrees.

<u><dip-mean>, <dip-sigma></u>

These variables are the mean and standard deviation of a uniform distribution for dip, in degrees.

<u><rake-mean>, <rake-sigma></u>

These variables are the mean and standard deviation of a uniform distribution for rake, in degrees

FILE TYPE

Station File . . . table of network stations and their locations.

CREATED BY

User.

USER BY

Program **synwav**, **anlyst**.

DESCRIPTION

This file contains the names and geographic locations of the stations in a seismic network. It is an ASCII file consisting of records separated by new-lines. The file contains one record for each station. Each record contains four data items in Fortran 77 "free" format (i.e., 'read *'). These items are (from left to right):

1. Station identifier (a character string).

2. Station code (an integer). (This code is for future use. It is presently read and ignored. It must be included in the file, however, so as to pacify the Fortran 77 free format utility.)

3. Station latitude (degrees north of equator).

4. Station longitude (degrees east of Greenwich).

Additional items on any station record are overlooked (and so may be used for documentation).

EXAMPLE

Here's a station file for a network of stations which are either in Ethopia or near large American universities:

AAE	-1	9.0292	38.7656	Addis Ababa, Ethopia
AAM	-1	42.2997	-83.6561	Ann Arbor, Michigan
SCP	-1	40.7950	-77.8650	State College, Pennsylvania

FILE TYPE

Structure File . . . a layered earth structure model used for surface wave calculations.

CREATED BY

User.

USED BY

Program **synwav**.

DESCRIPTION

This file contains the parameters of a plane layered earth model which is used by **synwav** for calculating surface wave responses. It is an ASCII file consisting of records separated by new-lines. The data are in Fortran 77 "free" format (i.e., 'read *'). Therefore, arbitrary white-space may be used to separate the items on each record (including extra new-lines).

The contents of the file, record by record, are as follows:

Record 1:
< comment >

Record 2:
< num-of-layers > < units-flag >

Record 3:
< thickness$_1$ > < α_1 > < β_1 > < ρ_1 > < qβ_1 > < dummy >

Record 4:
< thickness$_2$ > < α_2 > < β_2 > < ρ_2 > < qβ_2 > < dummy >

. . .

Record 2 – n:

< thickness$_n$ > < α_n > < β_n > < ρ_n > < $q\beta_n$ > < dummy >

In the above, subscript n stands for the variable < num-of-layers >

The meanings of the above variables follow.

<u>< comment ></u>.

A character string of 80 characters or less.

<u>< num-of-layers ></u>.

Number of layers in the earth structure model.

<u>< units-flag ></u>.

If < units-flag > is a non-zero integer, then the input values of < thickness$_i$ >, < α_i >, < β_i > and < ρ_i >, $i = 1, \ldots, n$, are multiplied by 1000. If < units-flag > is zero, no action is taken. It is an error to have < units-flag > be a non-integer.

<u>< thickness$_i$ ></u>

Thickness of the i^{th} layer (meters)

<u>< α_i ></u>

P wave velocity of the i^{th} layer (meters second)

<u>< β_i ></u>

S wave velocity of the i^{th} layer (meters second)

<u>< ρ_i ></u>

Density of the i^{th} layer (kg m^3)

< $q\beta_i$ >

Shear Q of the i^{th} layer.

< dummy >

A number which is read and ignored. It must be included so as to pacify the Fortran free format utility.

EXAMPLE

Here is an example of a structure file:

Standard East Kazakh Structure.

```
11   1
 1.1   5.0   2.7   2.1   150.0   0
25.0   5.9   3.2   2.5   250.0   0
19.0   6.8   3.7   2.8   400.0   0
20.0   8.1   4.5   3.3   600.0   0
15.0   8.2   4.5   3.3   600.0   0
20.0   8.0   4.4   3.3   100.0   0
30.0   7.8   4.2   3.2    90.0   0
30.0   7.8   4.2   3.2    90.0   0
40.0   7.8   4.2   3.2    90.0   0
20.0   8.0   4.4   3.3   100.0   0
80.0   8.5   4.7   3.5   200.0   0
```

FILE TYPE

Table File . . . tabulation of travel-time and amplitude versus distance and focal depth, for a particular body wave.

CREATED BY

User.

USED BY

Program **synwav**, **anlyst**.

DESCRIPTION

This is a binary file containing variable length records. It contains a tabulation of travel-time and amplitude for a given body wave (e.g., P), sampled on a rectangular grid in focal depth/epicentral distance space.

The content of the file, record by record, is as follows:

Record 1:
<num-of-depth-samples>

Record 2:
$\langle z_1 \rangle \langle z_2 \rangle \ldots \langle z_m \rangle$

Record 3:
<num-of-distance-samples>

Record 4:
$\langle x_1 \rangle \langle x_2 \rangle \ldots \langle x_n \rangle$

Record 5:
$\langle T_{11} \rangle \langle A_{11} \rangle \langle T_{21} \rangle \langle A_{21} \rangle \ldots \langle T_{n1} \rangle \langle A_{n1} \rangle$

Record 6:

$<T_{12}>$ $<A_{12}>$ $<T_{22}>$ $<A_{22}>$ . . . $<T_{n2}>$ $<A_{n2}>$

. . .

Record 4 – m:

$<T_{1m}>$ $<A_{1m}>$ $<T_{2m}>$ $<A_{2m}>$ . . . $<T_{nm}>$ $<A_{nm}>$

End-of-file

In the above, subscripts m and n stand for the variables <num-of-depth-samples> and <num-of-distance-samples>, respectively.

The meanings of the above variables follow

<num-of-depth-samples>.

This is the number of sample points with respect to event focal depth. (Fortran type 'integer'.)

$<z_i>$.

The value of the i^{th} sampling depth (kilometers, increasing downward). It is assumed that $<z_1>$ is the earth's surface and that $<z_{i-1}> \leq <z_i>$. (Fortran type 'real'.)

<num-of-distance-samples>.

This is the number of sample points with respect to event-station epicentral distance. (Fortran type 'integer'.)

$<x_i>$

The value of the i^{th} sampling distance (degrees). It is assumed that $<x_{i-1}> \leq <x_i>$. (Fortran type 'real'.)

$\langle T_{ij} \rangle$

The travel time (seconds) at the point $\langle x_i \rangle$, $\langle z_j \rangle$. (Fortran type 'real'.)

$\langle A_{ij} \rangle$

The peak-to-peak amplitude (microns) at the point $\langle x_i \rangle$, $\langle z_j \rangle$. The amplitude table is not required to be normalized for an event of a particular size (see manual entry "Reference File"). (Fortran type 'real'.)

Notes:

The travel time and amplitude values at the sample points are normally non-negative numbers. A negative value is interpreted to mean that the quantity is *undefined*.

The programs which use this file assume that the travel time and amplitude at an arbitrary distance and depth are obtained through interpolation between the given sample points. Values of travel time and amplitude outside the sample grid are not defined; i.e., for $z < \langle z_1 \rangle$, $z > \langle z_m \rangle$, $x < \langle x_1 \rangle$ or $x > \langle x_n \rangle$. Values are also not defined in an interval which is adjacent to an "undefined" (negative) sample.

A discontinuity in travel-time or amplitude with respect to distance or depth may be represented through the device of zero width intervals (e.g., $\langle x_i \rangle = \langle x_{i-1} \rangle$).

IV. REFERENCES

Harkrider, D. G. (1970). "Surface Waves in Multilayered Media II. Higher Mode Spectra and Spectral Ratios from Point Sources in Plane-Layered Earth Models," *BSSA*, *60*, pp. 1937-1987.

Lomnitz, C. (1966). "Statistical Prediction of Earthquakes," *Reviews of Geophysics*, *4*, pp. 377-393.

Murphy, J. R. and D. G. Lambert (1985). "An Assessment of Seismic Discrimination Capability with Respect to Small Events in the Pamir-Hindu Kush Region (U)," Final Technical Report submitted to the Defense Advanced Research Projects Agency, SSS-CR-86-7455, Contract No. F08606-84-C-0013. (S)

APPENDIX A

DISTRIBUTION OF EARTHQUAKE HYPOCENTERS. RECURRENCE INTERVALS AND MOMENTS

In this appendix, we describe in detail the distributions used to calculate source parameters for the earthquake catalog generated by the EVENTS program. These parameters are:

1. Epicenter
2. Depth
3. Slip vector orientation
4. Scalar moment
5. Origin time.

A 1 DISTRIBUTION OF EARTHQUAKE EPICENTERS

Epicenters are distributed over boxes on the surface of the globe Denote by $P_j = (\theta_j, \phi_j)$, $j = 1,2,3,4$, the colatitude-longitude pairs at the corners of the box, as shown in Figure A.1. The lines connecting the corners are great circles and intersect at right angles. The indeces increase counter-clockwise from P_1. The arcs connecting P_i to P_j have length ℓ_{ij} and the azimuth (clockwise from north) of P_j from P_i is α_{ij}. The positions P_1 and P_2 and arc length ℓ_{12} are specified by the user.

The program initially finds α_{12} and ℓ_{12} from a standard distance-azimuth routine. Then, if RV is a random variable uniformly distributed over [0,1] the quantities

$$\rho_{12} = RV \bullet \ell_{12}$$

$$\rho_{14} = RV \bullet \ell_{14}$$

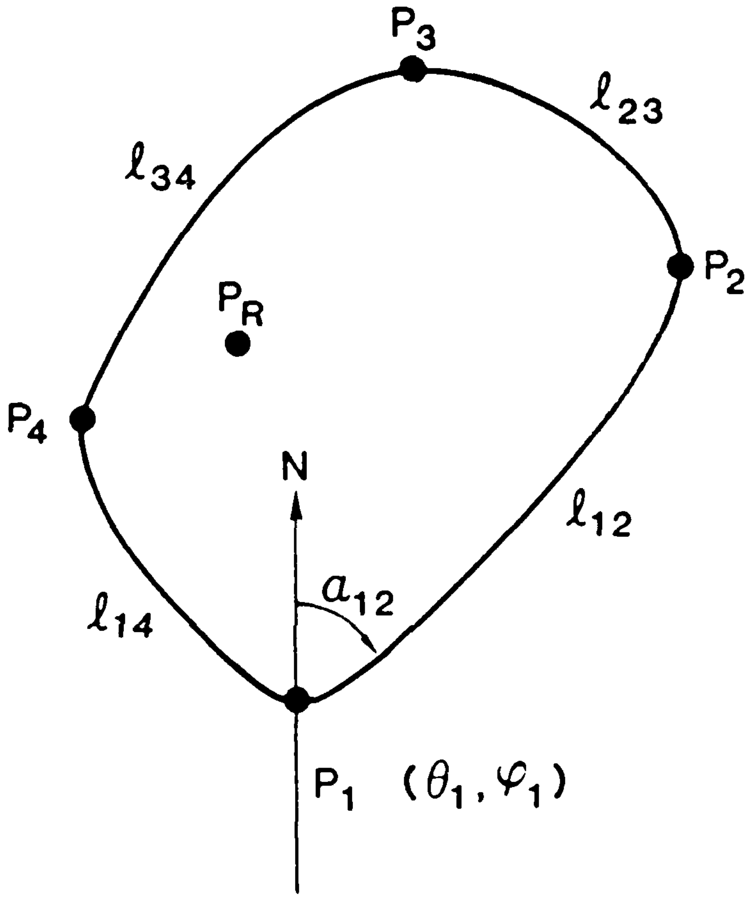

Figure A 1 The box containing epicenters is shown. Arcs are great circles of length ℓ_{ij} intersecting at right angles at points P_j with colatitude-longitude pairs (θ_j, ϕ_j). The meridian through P_1 is shown to illustrate the angle α_{12}.

are calculated. A different realization of the RV is used for ρ_{12} and ρ_{14}. The required coordinate pair $P_R = (\theta_R, \phi_R)$ is given by

$$\theta_R = \cos^{-1} [\cos(\theta_1) \cos(\Delta_{1R})$$

$$- \sin(\theta_1) \sin(\Delta_{1R}) \cos(\alpha_{12} - \alpha_{1R})]$$

$$\phi_R = \phi_1 - \sin^{-1} [\sin(\Delta_{1R}) \sin(\alpha_{12} - \alpha_{1R}) \sin(\theta_R)]$$

where

$$\Delta_{1R} = \cos^{-1} [\cos(\rho_{12}) \cos(\rho_{14})]$$

$$\alpha_{1R} = \sin^{-1} [\sin(\rho_{14}) \sin(\Delta_{1R})]$$

A.2 DISTRIBUTION OF EARTHQUAKE DEPTHS

In the program, the cumulative number of events occurring at or below a particular depth is piecewise linear. Denote by N_i the values of the cumulative distribution at depths Z_i, with $Z_1 = 0$ (specified by the user) and by RV a random variable uniformly distributed on [0,1]. Then the source depth Z_s is found from

$$Z_S = Z_j + (N_R - N_j) \left[\frac{Z_{j+1} - Z_j}{N_{j+1} - N_j}\right]$$

where $N_R = RV \bullet N_1$ and j satisfies $N_j \le N_R < N_{j+1}$

A.4 REFERENCES

Hanks, T. C. and D. M. Boore (1984). "Moment-Magnitude Relations in Theory and Practice," *J. Geophy. Res., 89 (B7)*, pp. 6229-6235.

Lomnitz, C. (1966). "Statistical Prediction of Earthquakes," *Reviews of Geophysics, 4*, pp. 377-393.

APPENDIX B

SYNWAV FORMULATIONS AND NUMERICAL METHODS

This appendix describes the mathematical formulations and numerical methods used by the SYNWAV program to compute synthetic seismograms. It is divided into two parts, devoted to body and surface waves. In each case, the earthquake is modeled as a point double couple source with a simple time history.

B.1 SYNTHETIC BODY WAVE SEISMOGRAMS

The vertical displacement spectrum at a [illegible] the product of a source excitation term times the product of transfer functions which quantify the effects of propagation and the recording instrument [illegible]

$$U(\omega) = \sum_{i=1}^{N} S_i(\omega, \theta, \phi)\, T^S(\omega, \theta)\, T^M(\omega)\, T^R(\omega)\, A(\omega) \ldots \quad [illegible]$$

$U(\omega)$ [illegible]

$S(\omega, \theta, \phi)$ [illegible]

$T(\omega)$ [illegible]

$T^M(\omega)$ [illegible]

$T^{(R)}(\omega)$ is the receiver region transfer function which propagates a wave impinging on the receiver region form below to the earth's surface as either vertical, radial or transverse displacement

$A(\omega)$ the anelastic attenuation operator

$I(\omega)$ the recording instrumentation response

For the SYNWAV module, we have assumed that the mantle transfer function obeys geometric ray theory, that is

$$T^M(t) = R^{-1}\delta(t-t_0) \qquad (B-2)$$

where R^{-1} is a geometric spreading factor and t_0 is the travel time. The code finds the values of R^{-1} and t_0 from bilinear interpolation of tables of $R^{-1}(r,z)$ and $t_0(r,z)$ where r is the angular distance and z is the focal depth. The interpolation routines also return the phase velocity

$$p = dt_0/dr \qquad (B-3)$$

which is used in subsequent calculations.

The source functions

for the P-SV problem and

$$\underset{=}{S}\ (\omega,\ \theta,\ \phi,\ \phi_S,\ \lambda,\ \delta) = \begin{bmatrix} a_U^{SH} \\ \\ a_D^{SH} \end{bmatrix}$$

for the SH problem, are the displacement spectra of the up and down going waves at the source. The subscripts "U" and "D" indicate up and downgoing waves, respectively. The orientation of the double-couple is specified by its strike ϕ_S, dip δ and rake λ.

We use the formulation given by Aki and Richards (1980) for the source strength of a point double-couple force:

$$a^P = \frac{1}{4\pi\rho_S\alpha_S^3}\left[\gamma \cdot \underset{=}{\dot{M}} \cdot \gamma\right]$$

$$a^{SV} = \frac{1}{4\pi\rho_S\beta_S^3}\left[\hat{p} \cdot \underset{=}{\dot{M}} \cdot \gamma\right] \qquad \text{(B1.4)}$$

$$a^{SH} = \frac{1}{4\pi\rho_S\beta_S^3}\left[\hat{\phi} \cdot \underset{=}{\dot{M}} \cdot \gamma\right]$$

where the vectors (γ, $\hat{p}$, $\hat{\phi}$) form a coordinate system moving with the array with γ pointing along the ray and $\hat{\phi}$ horizontally and normal to the direction of ray travel. The tensor $\dot{M}$ is the time rate of change of the moment tensor. In a coordinate system (x, y, z) whose unit vectors point north, east and down, the ray vectors are

$$\gamma = \sin\theta \cos\phi \, x - \sin\theta \sin\phi \, y - \cos\theta \, z$$

$$p = \cos\theta \cos\phi \, x - \cos\theta \sin\phi \, y - \sin\theta \, z$$

$$\phi = \sin\phi \, x - \cos\phi \, y.$$

The values of θ are computed from

$$\theta = \sin^{-1} (\alpha_S / c)$$

for the downgoing P wave (α_S is α at the source and c is the horizontal phase velocity), and

$$\theta = \pi - \sin (\alpha_S / c)$$

for the upgoing P wave. Similar expressions hold for the S waves. The components of the moment tensor in this coordinate are

$$M_{xx} = M_O (\sin\gamma \cos\lambda \sin 2\phi_S - \sin 2\delta \sin\lambda \sin 2\phi_S)$$

$$M_{xy} = M_{yx} = M_O (\sin\delta \cos\lambda \cos 2\phi_S - 1/2 \sin 2\delta \sin\lambda \sin 2\phi_S)$$

$$M_{xz} = M_{zx} = -M_O (\cos\delta \cos\lambda \cos\phi_S - \cos 2\delta \sin\lambda \sin\phi_S)$$

$$M_{yy} = M_O (\sin\delta \cos\lambda \sin 2\phi_S - \sin 2\delta \sin\lambda \cos^2 \phi_S)$$

$$M_{yz} = M_{zy} = - M_O (\cos\delta \cos\lambda \sin\phi_S - \cos 2\delta \sin\lambda \cos\phi_S)$$

$$M_{zz} = M_O \sin 2\delta \sin\lambda$$

where $M_O = M_O m(\omega)$, and M_O is the scalar moment. We have chosen a simple form of the earthquake spectrum $m(\omega)$ which incorporates the effects on the far field time history of fault dimension and stress drop. the functional form is

$$m(\omega) = \left[\frac{\sin \xi}{\xi} e^{-i\xi}\right]^2 \qquad \text{(B1.5)}$$

with

$$\xi = \frac{1}{4} \omega \tau$$

The characteristic time τ is given by

$$\tau = 2L/\beta$$

which depends on the source dimension L through the relation

$$L = \left(\frac{M_0}{\Delta\sigma}\right)^{1/3}$$

where $\Delta\tau$ is the dynamic stress drop, set to 10^7 Pascals (100 bars) in our calculations.

SYNWAV currently assumes that the source and receiver region transfer function $T_j^{(S)}(\omega)$ and $T^R(\omega)$ are simply equal to one. The source and receiver regions do not introduce individual distortions to the waveform. The decay rate (R^{-1}) tables provide relative amplitudes of the phases P, pP and S.

The anelastic attenuation operator is the one derived by Futterman (1962), given by

$$A(\omega) \quad \exp[\, ft^* (\pi \cdot 2 \ln(1000 f)) \text{[illegible]}$$

where f is frequency (ω = $2\pi f$).

B 2 SYNTHETIC SURFACE WAVE SEISMOGRAMS

Because surface waves are dispersed, it is necessary to compute a complete time series at each value of range. At a given range, source depth and orientation, the surface wave displacement spectrum is computed from (Harkrider, 1970)

$$u(\omega, r, \phi) = \frac{X(\omega, \phi, h_s)\; A_R(\omega)}{\sqrt{2\pi\omega C(\omega)\, R_e \sin\left(r / R_e\right)}}\; S(\omega) \qquad \text{(B2.1)}$$

$$\exp\left[i\frac{\pi}{4} - ik(\omega)r - \gamma r\right] \mathcal{E}(\omega)\; I(\omega)$$

where

ω	$2\pi f$ where f is frequency,
ϕ	the azimuth measured clockwise from North
h_s	the source depth
$X(\omega, \phi, h_s)$	a source excitation function
$S(\omega)$	the source spectrum
$\mathcal{E}(\omega)$	a function depending on the desired component of displacement, vertical, radial or transverse
R_e	the earth's radius
$C(\omega)$	the phase velocity
$I(\omega)$	[illegible]
$\gamma(\omega)$	the [illegible] attenuation [illegible]

$A_R(\omega)$ = the structure excitation function.

$I(\omega)$ = the instrument response.

We assume that for long-period teleseismic surface waves the source spectrum may be written in the simple form

$$S(\omega) = -M_0$$

where M_0 is seismic moment. The source excitation functions are

$$X(\omega,\phi) = d_0 - i[-d_1 \sin(\phi-\phi_S) - d_2 \cos(\phi-\phi_S)$$

$$- d_3 \sin 2(\phi-\phi_S) - d_4 \cos 2(\phi-\phi_S) \qquad \text{(B2.2)}$$

where ϕ_S is the strike (measured clockwise from North). The coefficients d are dependent on dip λ and rake δ and are listed in Table B2.1. The dip is measured down from the horizontal and the rake is measured counterclockwise from the horizontal in the plane of the fault. The eigenfunctions, referenced in Table B2.1, are those defined by Harkrider (1970).

The function $\mathcal{E}(\omega)$ is given by

$\mathcal{E} = -1$ for vertical component Rayleigh wave (positive up)

$\mathcal{E} = ie(\omega)$ for radial component Rayleigh wave, where e is the ellipticity.

$\mathcal{E}$ for Love Wave (transverse component)

B.3 REFERENCES

Aki, K. and P. G. Richards (1980). *Methods of Quantitative Seismology*. Two Volumes. W. H. Freeman and Company. San Francisco. California.

Futterman, W. I. (1962). "Dispersive Body Waves." *J. Geophys. Res.*, *67*. pp. 5279-5291.

Harkrider. D. G. (1970). "Surface Waves in Multilayered Media II. Higher Mode Spectra and Spectral Ratios from Point Sources in Plane-Layered Earth Models." *BSSA*, *60*. pp. 1937-1987

TABLE B2.1

SURFACE WAVE RADIATION PATTERN COEFFICIENTS FOR A DOUBLE-COUPLE SOURCE

Coefficient	Wave Type: Love	Wave Type: Rayleigh
d_0	0	$1/2 \sin\lambda \sin 2\delta\, B$
d_1	$1/\mu \cos\lambda \cos\delta\, E_2$	$1/\mu \sin\lambda \cos 2\delta\, E_4$
d_2	$-1/\mu \sin\lambda \cos 2\delta\, E_2$	$1/\mu \cos\lambda \cos\delta\, E_4$
d_3	$1/2 \sin\lambda \sin 2\delta\, E_1$	$-\cos\lambda \sin\delta\, E_1$
d_4	$\cos\lambda \sin\delta\, E_1$	$1/2 \sin\lambda \sin 2\delta\, E_1$

where B in the expression for d_0 is

$$B = \left(4\frac{\beta^2}{\alpha^2} - 3\right) E_1 - \frac{2}{\rho\alpha^2} E_3$$

and $E_j = E_j(\omega, h_s)$ are the eigenfunctions

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